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Recurrence of heavy precipitation, dry spells and deep snow cover in Finland based on observations

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The recurrence of heavy precipitation, dry spells and deep snow cover were estimated based on observations at about ten stations in Finland during about five decades. The 10-year return levels were assessed by means of the so-called "peak over threshold" (POT) method. The return levels of the annual maximum snow depth ranged from about 65 cm in southwestern Finland to about 110 cm in Lapland. On average once in ten summers, there is likely to be a 40-day period with at most 10 mm of accumulated rain, and a period of about 75 days with less than 50 mm of rain. The average 10-year return level estimate at a fixed site was 50 ± 8 mm for daily precipitation and 139 ± 9 mm for monthly precipitation. In comparison, additional material, consisting of monthly precipitation data at about 200 stations during the past 50–150 years, suggested that once in a decade the monthly precipitation somewhere in Finland exceeds 240 ± 12 mm. The difference demonstrated the lower likelihood of an extreme event at a certain site compared with the probability that such an event occur somewhere in the country. Climate change may alter these return levels in the future.

Introduction

According to the Köppen-Trewartha (K-T) classification, the land areas around the Baltic Sea are temperate or sub-arctic climate zones where the precipitation is, on average, moderate in all seasons (Castro *et al*. 2007). However, even in this moderate climate, there are periods with excessive precipitation and, on the other hand, several months with almost no precipitation at all. In Finland, for example, although summer 2006 was exceptionally dry, recent years have seen periods of torrential precipitation, breaking monthly and daily precipitation records. Controlled by precipitation and air temperature during the winter-half of a year, snow cover has also experienced large temporal and spatial variations. Similar examples can be found in other Baltic countries and elsewhere in Europe (*see* Trenberth *et al*. 2007).

Extreme events characterized by scanty or excessive precipitation or snow cover may have considerable environmental and socio-economic consequences. Abundant snow raises the costs of road clearance and imposes loads on the roofs of buildings and crowns of trees, while lack of snow is harmful for ski resorts and for hibernating plants and animals. Torrential rainfall increases soil erosion and chemical leaching, and may result in flooding. On the other hand, a prolonged deficit of precipitation decreases surface- and groundwater levels and can bring severe problems with water availability. For example, the drought in Finland in 2002/2003 had adverse effects on the environment and resulted in considerable economic losses, largely because of reductions in hydropower production but also due to impacts on buildings and on household water supply (Silander and Järvinen 2004).

In various sectors of society, more information is needed about the probability of extreme climate events. In media reports and public debate, the occurrence of rare, intense and/or severe climate events is frequently linked with human-induced global warming, either incorrectly as proof of climate change, or more suitably as a demonstration of events that may possibly be more common in the future. To be able to study the statistical significance of potential local or regional climate trends and to judge whether or not the trends are consistent with the null-hypothesis of no anthropogenic contribution, the limits of natural climate variability at different spatial and temporal scales should be known as accurately as possible. Knowledge about the frequency of extreme and rare weather events is inadequate due to relatively short observational time series. Rare events are so few and unevenly distributed, that long-term trends in their frequency and intensity are difficult to identify.

In the Fourth Assessment Report (AR4) of Intergovernmental Panel on Climate Change (IPCC), Trenberth *et al*. (2007) reported on widespread precipitation increases over mid- and high-latitude land areas of the northern hemisphere during 1901–2005. Similarly, the analysis of heavy precipitation events showed that rising trends dominate over the last three to five decades, especially during wintertime. However, as stated by Trenberth *et al*. (2007), many of the large-scale estimates of precipitation changes suffer from scarcity of data and lack of homogenous observational records. Therefore, regional trends may not be adequately described in these analyses. In order to provide more regional details and maximize the amount of data used in analyses, the BALTEX Assessment of Climate Change for the Baltic Sea Basin (BACC 2008) reviewed national studies that often have direct access to countrywide observational records. The studies showed that in the water catchments of the Baltic Sea the pattern of precipitation changes is highly variable in space and time. For example, a statistically significant increase in annual precipitation over the 20th century was observed in Sweden (e.g. Alexandersson 2004) and Denmark (Cappelen and Christensen 2005). In Finland, by contrast, the annual mean precipitation had notable inter-decadal variability during the 20th century but no significant long-term nationwide trend (Tuomenvirta 2004). Annual precipitation amounts measured at drainage level in Finland were generally larger in 1991–2000 than in 1961–1990, mostly due to wintertime increases (Hyvärinen and Korhonen (2003). Similarly, studies focusing on heavy precipitation events showed increases in magnitude during winter without any clear summertime trends (Haylock and Goodess 2004, Moberg *et al*. 2006, Kilpeläinen *et al*. 2008).

In the northern hemispheric (Lemke *et al*. 2007) and Fennoscandian (Moberg *et al*. 2005) scale the snow-covered area has decreased, especially since the late 1970s. Hyvärinen (2003) and BACC (2008) analyzed recent trends in the amount of snow in Finland during the last fifty years or so. According to BACC (2008), the mean maximum water equivalent of snow decreased by 29% in the Vantaanjoki drainage area in southern Finland while the Kemijoki drainage area in northern Finland experienced an increase by 11% from the period 1961–1990 to the period 1991–2005. Generally, snow storage in southern and southwestern parts of the county diminished while in northern and northeastern regions it increased. However, analysis of a 90-year long data set of snow depth in different parts of Finland by Solantie (2000) did not indicate persistent linear trends but large variations from decade to decade.

The objective of the study is to highlight some features of recurrence of meteorological drought, heavy precipitation and the annual maximum snow depth in Finland on the basis of observations. This study is by no means a comprehensive study describing all the features of precipitation extremes in Finland. However, the results presented here are earlier unpublished

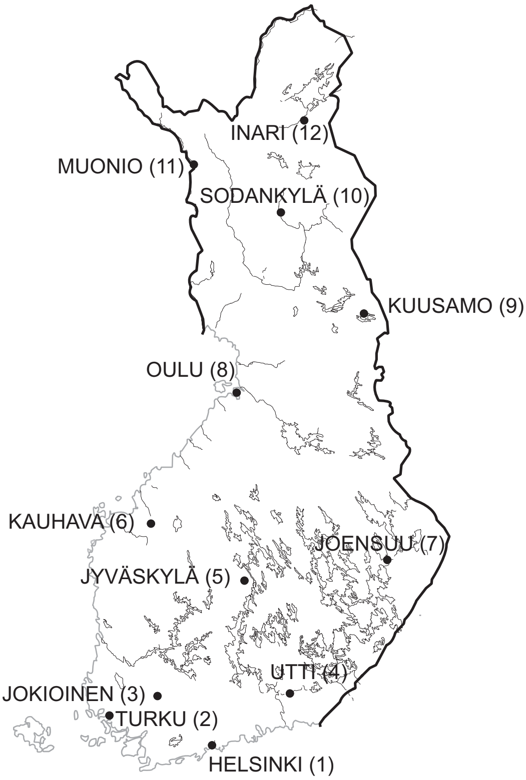

Fig. 1. The locations of the meteorological stations used in the study.

Table 1. The meteorological stations (name and a running number) and the periods (years) of data for monthly and daily precipitations and snow depths in estimates of 10-year return levels.

Station name	No.	Precipitation		Snow depth
		Monthly	Daily	
Helsinki	1	1844–2004	1958–2006	1950–2006
Turku	2	1950–2006	1950–2006	1950–2006
Jokioinen	3	1902–2004	1959–2006	
Utti	4	1945–2004	1959–2006	
Jyväskylä	5	1945–2004	1950–2006	1950–2006
Kauhava	6	1909–2004	1959–2006	
Joensuu	7	1933–2004	1947–1999	1950–2006
Oulu	8	1953–2004	1959–2006	1959–2006
Kuusamo	9	1908–2004	1959–1999	1959–2006
Sodankylä	10	1907–2004	1947–2006	1950–2006
Muonio	11	1909–2004	1959–2006	
Ivalo	12	1946–2004	1957–2000	1957–2006

results and increase our knowledge concerning the precipitation climate at high northern latitudes. As a part of the on-going Finnish Climate Change Adaptation Research Programme ISTO, return levels of various climate variables have been calculated, considering return periods between 10 and 500 years (Venäläinen *et al*. 2007). Here we concentrate on not very uncommon events, those with a 10-year return period. A subsequent paper will describe our findings for more extreme events and consider return levels of air temperature as well.

Material and methods

In Finland most of the daily data converted into digital form cover three to five decades. Observations of monthly precipitation amounts are available for longer time intervals. In this work the 10-year return level estimates for drought and heavy precipitation were calculated utilizing measurements made at 12 stations in different parts of the country and those for snow cover at eight sites during about 50 years (Fig. 1 and Table 1). For the sake of comparison, return levels of monthly precipitation were also assessed using all available monthly precipitation data, recorded at more than 200 stations. In that analysis all the observations were put together to get an estimate about the recurrence anywhere in Finland, whereas the analysis based on the 12 stations described the probability of occurrence in a certain site. The longest daily data set used in this study started in 1947 (Joensuu) and the longest monthly data set in 1844 (Helsinki). Actually, precipitation data in Helsinki since 1844 are available in digital form also on daily basis. This 163-year set of daily data in Helsinki was used for sensitivity tests, as discussed later.

In addition to daily and monthly precipitation, we considered the snow depth and the length of dry spells. The dry spells or periods with only a small amount of precipitation were characterized by the number of consecutive days during which the total sum of precipitation remained below a fixed threshold. Here we applied threshold values of 10, 25, 50, and 100 mm for accumulated precipitation and picked out the longest spells that started between 1 May and 31 August.

The return levels were estimated by means of the so-called "peak over threshold" (POT) method (Coles 2001), utilizing the extRemes toolkit software package developed in the National Center of Atmospheric Research (NCAR) (e.g. Katz *et al*. 2005, Gilleland and Katz 2006). Statistical analysis of extremes is founded on the theory of three types of probability distributions. The theory was first applied to fixed-interval extremes, or block maxima (e.g. the highest annual values) that follow the generalized extreme value (GEV) distribution. Afterwards, the POT method was developed as an alternative. It avoids the procedure of blocking but uses all data values exceeding a threshold to define the Generalized Pareto (GP) distribution. A drawback is the sensitivity of the results to the selected threshold. If the limiting value is too high, the remaining small amount of cases widens the uncertainty range of the results. On the other hand, if it is too low, the distribution fitted to the data may not represent truly extreme cases (e.g. Coles 2001).

The extRemes toolkit software package includes a tool that helps to find the most appropriate thresholds to be used in the POT method, and also provides 95% confidence intervals for the return levels. The most appropriate threshold can be searched either using a method know as "Mean residual plot" or by fitting data to GPD over a range thresholds. When using the "mean residual plot" that is known also as "mean excess plot" the idea is to find the lowest threshold where the plot is nearly linear. The second method for trying to find a threshold requires fitting data to the GPD distribution several times, each time using a different threshold. Stability of the parameter estimate can then be checked.

The extRemes software package includes the selection of a most appropriate distribution for each dataset. The user can select the method with which the parameters of GP distribution are estimated. In the current study the method known as Nelder-Mead was applied.

To study the sensitivity of the results to the selected threshold, together with the effect of climate variability, Venäläinen *et al*. (2007) divided daily precipitation data in Helsinki from 1844–2006 into subsequent sets of 30 years and applied five different thresholds ranging between 5 and 11 mm for each period. The best estimates for the 50-year return level of daily precipitation were found to vary only slightly — at the maximum by ±5 mm (about ±8%) between the 30-year periods — without any systematic long-term trends. The greatest differences between the threshold values for a fixed 30-year data set appeared to be of the same magnitude. As regards the 95% confidence intervals, they expectedly got broader with increasing threshold but did not vary a lot from one 30-year period to another. It was concluded by Venäläinen *et al*. (2007) that daily precipitation levels occurring in Helsinki once in 50–100 years can be estimated with the accuracy of ±8 mm, when using a reasonable threshold and 150 years of data coverage. In this paper, the uncertainty ranges of 10-year return level estimates, based on observations during five decades, are comparable in magnitude.

Relatively short periods of observational time series make it difficult to estimate return levels of very extreme phenomena, i.e. those having return periods of several hundreds of years. Further challenges are caused by climate change. In addition to the 30-year periods, Venäläinen *et al*. (2007) examined a 16-year period of 1991–2006 and arrived at higher return level estimates for daily precipitation than on the basis of the previous 30-year spans in Helsinki. However, because the 95% confidence intervals were almost twice as broad as, and thus strongly overlapping with, the confidence intervals based on the previous longer periods of data and since just a single station was considered, it is far from possible to attribute the findings to climate change. Exploring sub-daily data at the same station in summers 1951–2000, Kilpeläinen *et al*. (2008) could not find clear trends either. In any case, climate change should be kept in mind as an additional source of uncertainty in the return level estimates.

Results

Among the 12 stations studied, the best estimates (95% confidence intervals in parentheses) for the 10-year return level of daily precipitation varied between 39 (35–45) mm and 57 (48–67) mm (Fig. 2). The corresponding monthly values were about three times as large, ranging from 121

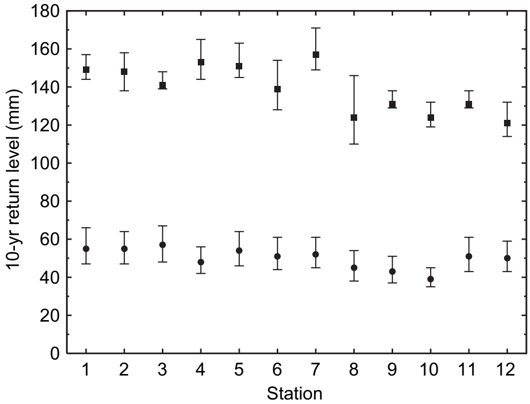

Fig. 2. The 10-year return level estimates with 95% confidence intervals for monthly (upper) and daily (lower) precipitation amounts at 12 measurement stations. *See* Fig. 1 for the location of the stations and Table 1 for the observational periods.

(114–132) mm to 157 (149–171) mm. The 12-station average of the return level estimates was 50 ± 8 mm for daily precipitation and 139 ± 9 mm for monthly precipitation. The return levels at the southern stations were typically somewhat higher than those at the northern ones; the annual mean precipitation in Finland generally decreases from the south to the north as well.

According to our estimates based on all available data from more than 200 stations, once in a decade the monthly precipitation somewhere in Finland exceeds 240 ± 12 mm. That return level is much higher than the corresponding value for a fixed location. The difference demonstrates the lower likelihood of an extreme event at a certain site compared with the probability that such an event occur somewhere in the country.

The 10-year return level estimate for the length of a summertime period with the precipitation sum of consecutive days remaining below 10 mm was 40 (34–46) days in Jokioinen (Fig. 3a). On average once in ten summers there is likely to be a period of 74 (68–87) days with only 50 mm of rain or a period of 100 days with not more than 65–105 mm of rain. These results for Jokioinen are rather typical for all the 12 stations. The variations between the different stations were very small for the threshold of 10 mm but increased rapidly with the increasing upper limit of accumulated rain amount (Fig. 3b). Considering the best estimates, one can see that the return level for 25 mm of rain at one station may be almost as large as the return level for 50 mm at another location. Quite large differences between the stations for the high thresholds may be partly caused by spatial variations of climate,

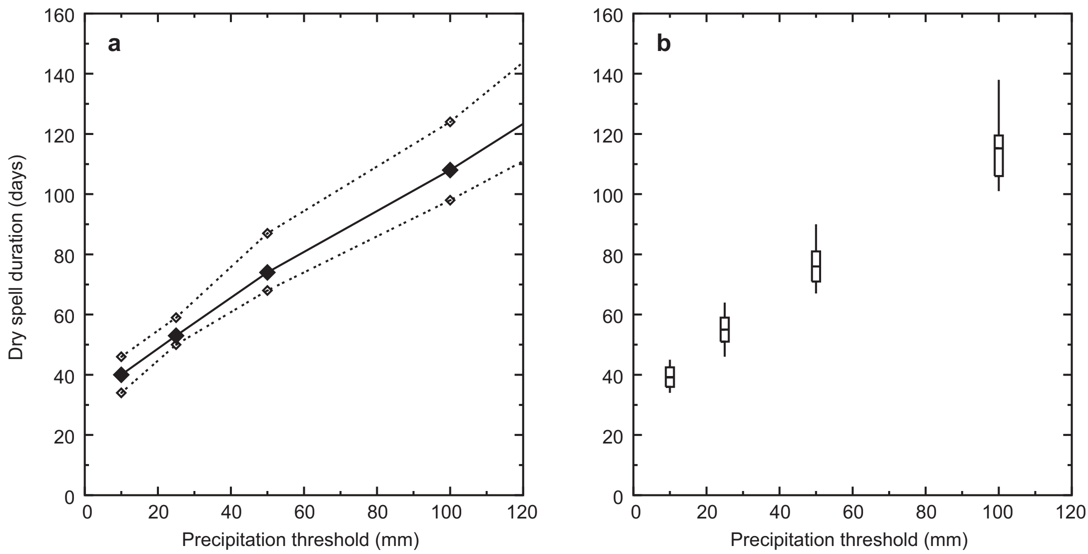

Fig. 3. The 10-year return levels for the duration of summertime spells with a small amount of precipitation, as a function of the accumulated precipitation thresholds (in mm). (**a**) The maximum likelihood estimates (solid line) and the 90% confidence intervals (dotted lines) for Jokioinen. (**b**) The variation of the maximum likelihood estimates among the studied 12 stations. Shown are (from bottom to top) the minimum, the 1st quartile, the mean, the 3rd quartile, and the maximum.

although in contrast to heavy precipitation, no clear south–north gradient could be found. However, the relatively short periods of data, about 50 years, increased the uncertainty.

The levels of annual maximum snow depth occurring once a decade or more seldom generally increased from southern to northern Finland (Fig. 4). However, the stations near the coast were characterized by a thinner snow cover than those inland. The return level estimates ranged from 65 (63–70) cm in Turku to 109 (106–128) cm in Sodankylä.

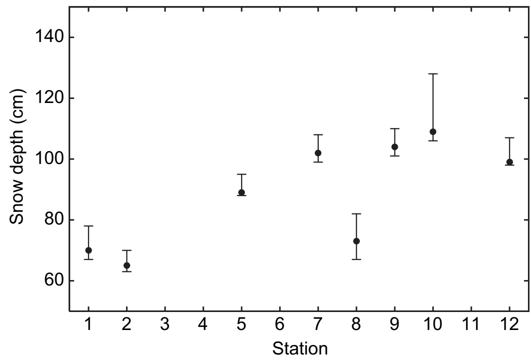

Fig. 4. The 10-year return level estimates with 95% confidence intervals for the annual maximum snow depth (cm) at 8 measurement stations. The locations of the stations and observational periods are given in Fig. 1 and Table 1, respectively.

Discussion

When we are estimating the recurrence of very rare events, e.g. probabilities of 1/1000, the length and quality of observations used as input in calculations is very crucial. Typically we have only a few decades of reliable meteorological observations and thus the return level estimates of very rare events can not be very reliable. As the most extreme cases belong to another population of events than the other cases there are no statistical methods that can describe these cases that have never occurred earlier or at maximum have one or two observations of these events. Here we studied events taking place once in ten years and thus the length of measurement time series is not as crucial as in more rare cases.

The differences in results between the locations are caused partly by the general climatological features and partly by the micrometeorological conditions. Typically the further north the site locates the colder the climate is and the less precipitation can occur there. Also the surrounding like the openness of measuring site has large influence on precipitation measurements. On open sites large share of precipitation never falls to precipitation gauge and thus the measurements underestimates. This is the case especially with snowfall. Snow depth measurements made at one location only at a observing stations can be regarded to be representative only for that very small area and at open sites snow drifting may cause large spatial variation on snow depth.

Despite of the many problems related to use of routine meteorological observations for the estimation of weather extremes this is still the best available data source for this kind of analyses.

Conclusions

Decision-making, including climate risk management and adaptation to climate variability and change and the potential impacts, should be based on the best available knowledge about the past, current and future climate. An important aspect in risk management is related to extreme and rare weather events. In Finland their recurrence has not been systematically examined based on a number of measurements stations and considering various climatic variables prior to the study by Venäläinen *et al.* (2007). Here we introduced some of their findings and discussed the 10-year recurrence of heavy daily and monthly precipitation, dry spells defined by various thresholds, and annual maximum snow cover. Challenges in studies of rare and extreme weather events are caused by the relatively short periods of observational time series and the ongoing climate change. In the future, the return levels are likely to alter. This should be kept in mind in various applications.

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